

Preface

This issue of the *IBM Journal of Research and Development* is devoted to the scientific aspects of electron transport in small structures. The articles contained here reflect only some of the current research interests and are not intended to be a comprehensive survey of all the scientific contributions that have been made to the field of very small structures. The July issue of the Journal will highlight the current lithographic technology associated with fabrication of small structures.

Over the past thirty years, IBM has contributed significantly to the technology and science associated with fabrication and characterization of very small electronic devices. Electronic miniaturization has been motivated by the need to increase the number of integrated circuits on a single chip, thereby lowering the manufacturing cost per device, decreasing the time for signal propagation between devices, and simplifying the interconnections between chips. The definition of the word "small" has, of course, changed over this period and has been linked to the available technology for device fabrication. In the late 1950s the minimum circuit dimension of $\sim 5 \mu\text{m}$ was obtained by using optical lithographic techniques. Electron-beam techniques were beginning to be used for sample fabrication with minimum dimensions of about $1 \mu\text{m}$ in the early 1960s. With the discovery in the mid-1960s of polymethyl methacrylate (PMMA), a very-high-resolution electron-beam photoresist, and the lift-off metallization process, the fabrication of wires with submicron dimensions became possible. PMMA is still one of the most widely used electron-beam resists, and single-layer structures and devices have been made with linewidths as small as $0.01 \mu\text{m}$. The rapid advances in e-beam lithographic techniques were accompanied by the development of new semiconductor devices in silicon and gallium arsenide. The first $1\text{-}\mu\text{m}$ silicon bipolar and MESFET or Schottky barrier devices, developed in IBM research laboratories in the late 1960s, were at that time the highest-frequency transistors ever reported. Acoustic drivers used in delay line applications and superconducting lines with dimensions as small as $0.3 \mu\text{m}$ and $0.1 \mu\text{m}$, respectively, were in use at Research in the late 1960s.

In parallel with technological innovations, fundamental questions were raised concerning our understanding of the physics of small devices. It was evident that the classical model of electron transport in devices did not accurately describe small objects, and that a clarification of the difference between the properties specific to a given sample and those that follow from averaging over a large collection of macroscopically identical but microscopically different samples needed to be made. In the case of small samples, there must be some size scale where we can no longer predict the electrical properties of very small devices, since

each nominally identical sample exhibits different properties depending upon the nature, number, and distribution of the scattering centers. In the early 1970s a theoretical analysis provided an understanding of some of these issues by showing how the threshold voltage in field-effect transistors could vary in nominally identical devices when the number of impurities contained within each device was made small. An important unanswered question: At what size scale ξ will the quantum-mechanical wavelike properties of the electrons affect the transport properties of a small device? It was generally believed that this size scale should be comparable to the average distance the electron travels before scattering from an impurity. The reason for this: Every time the electron scatters from an impurity, the phase of its wave function is altered. As with all wave phenomena, if the phase information in the wave function becomes randomized, interference effects vanish. Elastic scattering from grain boundaries, impurities, sample walls, etc., does not introduce phase randomization into the wave function of the electron—only inelastic scattering of the electrons causes phase randomization. Inelastic scattering rates decrease as the temperature is lowered; thus, the size scale ξ over which quantum-mechanical interference effects are important can become arbitrarily large.

All of the papers in this issue describe portions of our current understanding of the consequences of long-range electronic phase coherence in small devices. A new and exciting area of scientific research has been opened up by the theoretical and experimental work leading to the discoveries of periodic magnetic field effects in rings and sample-specific random behavior of the conductance in wires and MOSFET devices as either the magnetic field or the Fermi energy of the electrons is varied. These investigations will eventually answer the question of how small device dimensions can become before quantum mechanics and the lack of ensemble averaging will limit the performance of circuit chips.

In 1957, Landauer, in the first volume of this Journal, demonstrated that there were strikingly significant spatial variations near localized sources of electronic scatterers. He also pointed out that the electrical resistance associated with electronic scattering from a single impurity or barrier in one dimension was proportional to $(h/2e^2)R/(1 - R)$, where R is the quantum-mechanical reflection probability of the electron from the impurity (e is the charge of the electron, and h is Planck's constant). In the first paper of this issue, Landauer reviews some of his early arguments on the spatial variation of electrical currents in small samples within the framework of our current understanding of the physics of small structures. In addition, he clarifies some of his predictions concerning the vanishing of the electrical resistance in closed normal-metal loops, and the existence of a persistent current that varies periodically as the enclosed

magnetic flux is changed with a period given by the normal-metal flux quantum $\Phi_0 = h/e$. The role of electronic quantum coherence in establishing a persistent current in a nonsuperconducting ring in the presence of a magnetic field is treated in detail in the article by Cheung, Gefen, and Riedel; they show that for rings of macroscopic size containing a large number of elastic scattering sites, the effects of disorder and finite temperature are not as disruptive as first thought. The Landauer formula and its multichannel extensions have been the subject of some theoretical controversy. The article by Stone and Szafer reviews some of the history surrounding these controversies and presents a new derivation based upon linear response theory which demonstrates that Landauer-type formulas are obtainable from more conventional transport calculations. They also revisit the old question concerning whether the electrical resistance of a perfect conductor can really be zero, and discuss the role of electron reservoirs in establishing thermodynamic equilibrium. Kirtley, Washburn, and Brady present measurements of the surface potential of a thin normal-metal film using a scanning tunneling microscope in the presence of an applied current. They show that the potential is nearly zero within an individual grain and that most of the voltage drop occurs at the boundary between grains comprising the sample. This is the first direct measurement which demonstrates that in a room-temperature metal film the conventional Boltzmann picture for electrical transport breaks down.

Some recent theoretical ideas, as well as many of the experiments on the periodic and random quantum interference effects in normal metals, are reviewed by Washburn. In particular, he presents a discussion of nonlocal quantum interference effects, which was one of the most unexpected experimental discoveries in this field. We now understand that when the characteristic distance the electron wave propagates before losing phase coherence is larger than the spacing between voltage probes attached to the sample, the measured electrical properties have a nonlocal contribution. The effective sample size is not determined by the location of lithographically patterned probes, but rather by the properties of the electron itself. In fact, as shown in the article by Büttiker, the measured properties of any small sample in this phase-coherent regime depend upon how the measurement is made. The addition of voltage and current probes to a sample in classical physics does not change the properties of that sample, but in a small quantum-mechanically phase-coherent system, when appendages are added to the sample they become part of the sample. The electrons can and do travel into all the attached probes. Büttiker also explains one of the early mysteries associated with the lack of symmetry about zero magnetic field of the quantum interference properties of small systems, and derives the proper microscopic reciprocity relations appropriate for multiprobe devices.

Kaplan and Hartstein demonstrate that these new quantum interference effects are readily observable in the strongly conducting regime of any semiconductor device. They show that the current-voltage curves of any small device have nonlinear contributions arising from quantum interference effects. The article by Fowler, Wainer, and Webb discusses the wealth of new fluctuation phenomena discovered in very small MOSFET devices operated in the localized regime of transport, where quantum-mechanical tunneling from one localized state to another is the only mechanism by which electrons can propagate through the sample. A new type of zero-bias-voltage spectroscopy is discussed that allows the details of an individual localized state to be studied as a function of chemical potential or magnetic field. This technique is used to characterize the two main transport mechanisms in insulators, resonant tunneling and Mott variable-range hopping.

The understanding we have recently gained in the physics of electron transport in small structures inevitably leads to more questions. Can we build high-speed, low-power-dissipation, quantum-interference-effect transistors that will eventually be useful in our future technologies? Within the framework of our current technology, power dissipation is one of the major limitations controlling the future density of devices on a single chip. Making smaller high-power dissipative devices is not an acceptable solution; a new technology is required. Work has already begun in the area of coherent devices, and last year the first three-terminal normal-metal quantum interference device was fabricated at the IBM Thomas J. Watson Research Center. Other questions involving the effect of sample-specific behavior of small structures in the presence of the motion of a single impurity limiting the usefulness of quantum interference devices in VSLI applications need to be studied in some detail.

Regardless of the final verdict on the applicability of small structures in future technologies, the new understanding we have gained (and will continue to gain) about the physics of small devices has opened up a whole new field in condensed-matter physics. This area of investigation should eventually allow us to understand how the transition is accomplished from a single quantum-mechanical object to macroscopic collections of quantum-mechanical objects, and eventually to the everyday classical world.

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Guest Editors

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